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Influence of the Interface Quality on Magnetic Properties of $Fe_{20}Ni_{80}$/Tb–Co Films with Unidirectional Anisotropy

N.A. Kulesh*, K.G. Balymov and V.O. Vas'kovskiy

Department of Magnetism and Magnetic Nanomaterials, Ural Federal University,
Mira str. 19, 620002 Yekaterinburg, Russia

Influence of annealing on hysteresis properties of the soft magnetic layer in $Fe_{20}Ni_{80}/Tb_{26}Co_{74}$ and $Fe_{20}Ni_{80}/Ti/Tb_{26}Co_{74}$ films with unidirectional anisotropy was investigated. Modification of the interface by introduction of the ultrathin Ti spacer was demonstrated to improve stability of coercivity and exchange bias field. According to our assumption, the Ti spacer can act as a barrier preventing a thermally-induced diffusion between the magnetic layers. In order to verify this point grazing incidence X-ray fluorescent analysis was used. Comparison of two sets of data attributed to the samples with and without Ti spacer at different stages of annealing revealed decrease of the angular shift between Co and Ni dependences even after annealing at 70 °C for $Fe_{20}Ni_{80}/Tb_{26}Co_{74}$ and absent of any changes up to 300 °C for the $Fe_{20}Ni_{80}/Ti/Tb_{26}Co_{74}$ film. These results can be interpreted as an evidence of the low-temperature interface modification in form of diffusion-like process in the samples without Ti spacer.

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1. Introduction

Thin magnetic structures based on exchange coupled ferromagnetic and antiferromagnetic layers are of great interest due to the numerous applications in spintronics, magnetic sensors, and logical devices [1, 2]. Mechanism of the magnetic coupling often remains obscure because of complexity of magnetic frustrations and compositional gradients in the interface region [3, 4]. Introduction of magnetic or nonmagnetic spacers [5] as well as heat treatments [6] were demonstrated to be an effective way of modification of magnetic and magnetoresistive properties of sandwiches or multilayers. In this study we considered effect of annealing and introduction of ultrathin Ti spacer on magnetic properties of exchange coupled sandwiches based on amorphous ferrimagnetic $Tb_{26}Co_{74}$ and soft magnetic $Fe_{20}Ni_{80}$ layers with unidirectional anisotropy.

Grazing incidence X-ray fluorescent analysis (GIXRF) is relatively new but well established method for investigation of near-surface region [7]. As stand-alone technique or in pair with X-ray reflectometry (XRR) it was shown to be a powerful technique for analysis of interface roughness and interdiffusion of layers in thin films and multilayers [8]. In this study we used desktop spectrometer rather than traditional synchrotron-based setup and simple analytical procedure to obtain valuable qualitative information on interface quality of $Tb_{26}Co_{74}/Fe_{20}Ni_{80}$ bilayers.

2. Samples and methods

Samples were obtained by high-frequency ion sputtering of mosaic Tb–Co, alloyed $Fe_{20}Ni_{80}$ and Ti targets. For samples used for magnetic measurements thicknesses of Tb–Co and $Fe_{20}Ni_{80}$ layers were 110 nm and 50 nm, respectively. In order to prevent oxidation 11 nm Ti top layer was used. All films were deposited on glass substrates at presence of the uniform magnetic field of 100 Oe oriented parallel to the samples plane. In order to perform qualitative GIXRF analysis additional series of thinner films (thickness of each layer was 5 nm) were deposited under the same conditions on both glass and silicon substrates.

Stepped annealing of some samples was performed in vacuum chamber at residual pressure of 10^{-6} mm Hg. At each temperature samples were treated for 1 h. In order to avoid effect of mechanical stress relaxation in substrates during the heat treatment, preliminary 1 h annealing was performed at 300 °C before deposition of the films.

Vibrating sample magnetometer was used for magnetic measurements at room temperature.

According to the X-ray diffraction data Tb–Co layers were in amorphous, $Fe_{20}Ni_{80}$ layers in nanocrystalline state. Composition of Tb–Co layers was controlled by non-destructive total reflection X-ray fluorescent analysis (TXRF).

For GIXRF experiment Nanohunter TXRF spectrometer was used. All measurements were performed at maximum angle resolution available, which in our case was 0.01°. Air-cooling 50 W X-ray tube with Mo anode was used as a primary excitation source.

3. Results and discussion

In this work amorphous ferrimagnetic $Tb_{26}Co_{74}$ layer with magnetic moment of the rare earth sublattice dominating at room temperature and below was used. Due to the presence of technological magnetic field during the deposition process easy axis of the ferrimagnetic layer was oriented in film's plane [9].

*corresponding author; e-mail: nikita.kulesh@urfu.ru

Due to the ferromagnetic coupling between magnetic moments of Co sublattice and permalloy layer hysteresis loops of $Tb_{26}Co_{74}/Fe_{20}Ni_{80}$ films had stepped character with low-field and high-field jumps of magnetisation corresponding to magnetization reversal of $Tb_{26}Co_{74}$ and $Fe_{20}Ni_{80}$, respectively (see inset in Fig. 1a) [6]. Also it is possible to obtain hysteresis loop of the permalloy layer if magnetic field range does not exceed coercivity of the ferrimagnetic layer. Such loops were used to estimate coercivity H_c and exchange bias field H_e of the soft magnetic layer. Preliminary study of $Tb_{26}Co_{74}/Fe_{20}Ni_{80}$ films with unidirectional anisotropy demonstrated that hysteresis properties of permalloy layer depends strongly on the state of the interface, which can be changed by introduction of the spacer or heat treatment [5].

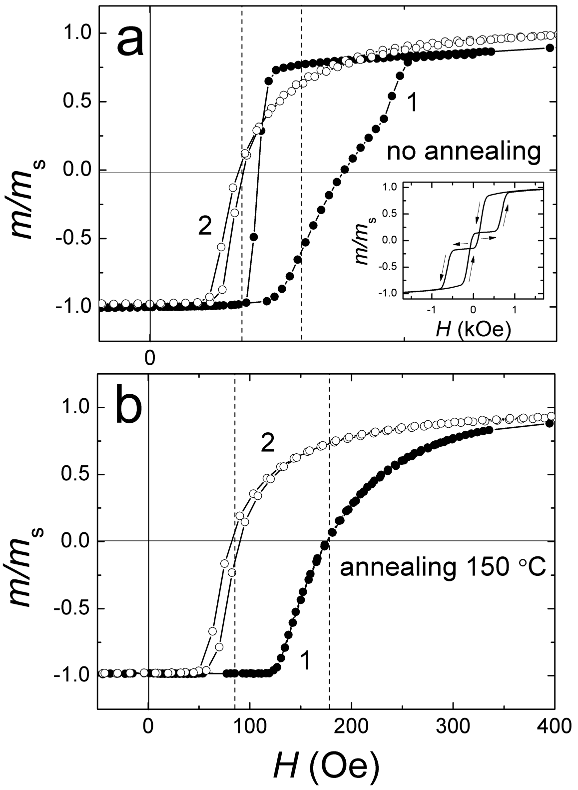

Fig. 1. Hysteresis loops of the $Fe_{20}Ni_{80}$ layer measured on $Tb_{26}Co_{74}/Fe_{20}Ni_{80}$ (curves 1) and $Tb_{26}Co_{74}/Ti(0.7\ nm)/Fe_{20}Ni_{80}$ (curves 2) samples before (a) and after (b) annealing at 150 °C. Major hysteresis loop with the direction of magnetisation reversal process indicated by arrows (insert in (a)).

In Fig. 1 hysteresis loops of the permalloy layer measured for samples $Tb_{26}Co_{74}/Fe_{20}Ni_{80}$ with and without 0.7 nm Ti spacer before and after annealing are presented. The hysteresis loop shape and high coercivity in Fig. 1a, curve 1 might indicate that the permalloy layer magnetization process takes place mainly by interfacial domain wall motion partially involving adjoining ferrimagnetic material (similar mechanism was described by Mauri et al. [3]). Highly asymmetrical shape of the loop was observed and described in [10].

As can be seen, annealing changes character of magnetisation reversal of the sample without Ti spacer dramatically, leading to the sharp decrease of H_c value. The last circumstance also affects H_e resulting the effective increase of the hysteresis loop shift.

Hysteresis loop of $Tb_{26}Co_{74}/Ti(0.7\ nm)/Fe_{20}Ni_{80}$ sample, on the other hand, after annealing remains practically the same. Low H_c value observed in Fig. 1a, curve 2 can be explained in terms of weakening of the interface exchange coupling due to the increase of effective distance at the interface [3] and preventing the interface domain wall from penetrating deeply into the $Tb_{26}Co_{74}$ layer.

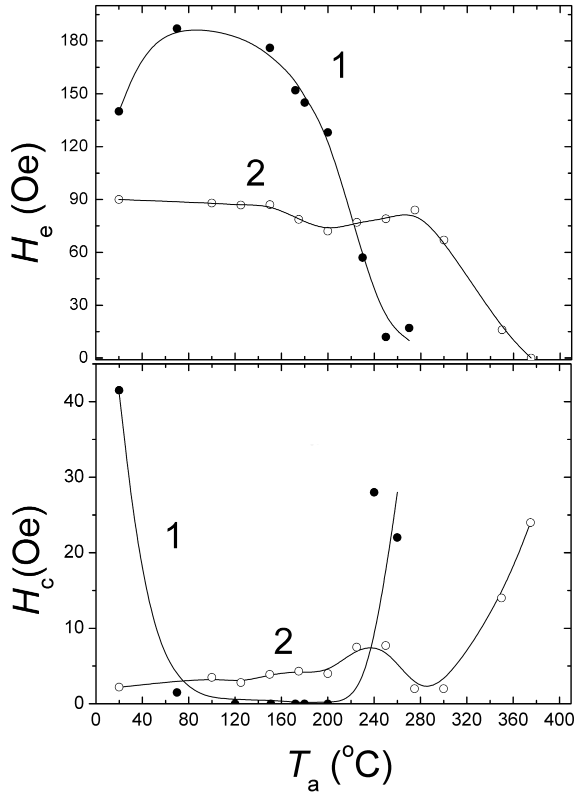

Fig. 2. Temperature dependences of exchange bias field H_e (a) and coercivity H_c (b) obtained on $Tb_{26}Co_{74}/Fe_{20}Ni_{80}$ (curves 1) and $Tb_{26}Co_{74}/Ti(0.7\ nm)/Fe_{20}Ni_{80}$ (curves 2) samples.

In Fig. 2 dependences of H_c and H_e on annealing temperature measured for samples with and without 0.7 nm Ti spacer are presented. For the $Tb_{26}Co_{74}/Fe_{20}Ni_{80}$ sample the very first annealing leads to sharp fall of coercivity and slight increase of H_e as was described above. Coercivity jump and fall of the exchange bias field following the annealing at temperatures exceeding 200 °C is more likely the evidence of diffusion process between the layers. For the sample with Ti spacer hysteresis properties of the permalloy layer remain stable after annealing at up to 300 °C. The last circumstance presumably can be explained as a consequence of the Ti spacer acting as a diffusion barrier.

4. Investigation of interlayer diffusion

In order to investigate changes in the interface region appearing as a result of annealing, GIXRF experiment on thin $Tb_{26}Co_{74}/Fe_{20}Ni_{80}$ and $Tb_{26}Co_{74}/Ti(0.7\ nm)/Fe_{20}Ni_{80}$ samples was performed. Due to the strong overlap of peaks corresponding to the main characteristic lines of Fe and Tb, only X-ray fluorescent yield of Co and Ni was considered. During the experiment angular dependencies of the X-ray fluorescent intensities of the corresponding element were measured and analysed in terms of angular shift between their maxima. The method used for estimation of the angular shift allowed us to obtain well-defined value (precision was limited by the angular resolution of 0.01) which was measured five times at each step of annealing. Data obtained on samples deposited on Si and SiO_2 substrates were similar, although dependences obtained for films on glass were noisier and less pronounced due to worse quality of the surface.

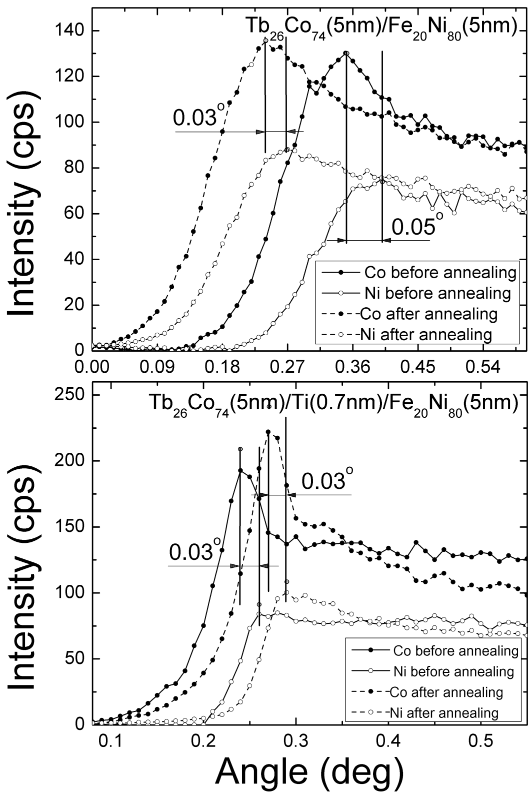

Fig. 3. Angle dependencies of X-ray fluorescent yield of Co and Ni obtained on $Tb_{26}Co_{74}$(5 nm)/$Fe_{20}Ni_{80}$(5 nm) and $Tb_{26}Co_{74}$(5 nm) /Ti(0.7 nm)/$Fe_{20}Ni_{80}$(5 nm) samples deposited on glass substrates before and after annealing at 300 °C.

In Fig. 3 example of angular dependencies of X-ray fluorescent yields of Co and Ni measured on as-deposited and annealed at 300 °C samples with and without Ti spacer are presented. Estimated values of angular shift are pointed out in the illustration for reading convenience. The dependences obtained before and after annealing differ from each other mostly by the angular shift, while being qualitativly the same.

Interestingly, almost the same angular shift was observed for $Tb_{26}Co_{74}/Fe_{20}Ni_{80}$ sample after the very first annealing at 70 °C. This fact as well as absent of any changes on similar film with Ti spacer points out the low temperature changes, which are most likely related to the diffusion process. Another possibility is a relaxation processes in the interface region, which lead to the substantial increase of the interface roughness and changes the angular shift in a similar way as diffusion does.

5. Conclusions

Influence of annealing on hysteresis properties of the $Fe_{20}Ni_{80}$ layer in $Fe_{20}Ni_{80}/Tb_{26}Co_{74}$ films with unidirectional anisotropy was investigated. Introduction of the Ti spacer was demonstrated to improve temperature stability of coercivity and exchange bias field of the permalloy layer. GIXRF experiment allowed us to detect low-temperature diffusion-like process in the samples without spacer and absent of any changes in the film with layers separated by Ti spacer for annealing at temperatures up to 300 °C.

Acknowledgments

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